nature climate change

LETTERS

PUBLISHED ONLINE: 1 APRIL 2012 | DOI: 10.1038/NCLIMATE1461

135 years of global ocean warming between the *Challenger* expedition and the Argo Programme

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Changing temperature throughout the oceans is a key indicator of climate change. Since the 1960s about 90% of the excess heat added to the Earth's climate system has been stored in the oceans[1,2]. The ocean's dominant role over the atmosphere, land, or cryosphere comes from its high heat capacity and ability to remove heat from the sea surface by currents and mixing. The longest interval over which instrumental records of subsurface global-scale temperature can be compared is the 135 years between the voyage of HMS *Challenger*[3] (1872–1876) and the modern data set of the Argo Programme[4] (2004–2010). Argo's unprecedented global coverage permits its comparison with any earlier measurements. This, the first global-scale comparison of *Challenger* and modern data, shows spatial mean warming at the surface of 0.59 °C ± 0.12, consistent with previous estimates[5] of globally averaged sea surface temperature increase. Below the surface the mean warming decreases to 0.39 °C ± 0.18 at 366 m (200 fathoms) and 0.12 °C ± 0.07 at 914 m (500 fathoms). The 0.33 °C ± 0.14 average temperature difference from 0 to 700 m is twice the value observed globally in that depth range over the past 50 years[6], implying a centennial timescale for the present rate of global warming. Warming in the Atlantic Ocean is stronger than in the Pacific. Systematic errors in the *Challenger* data mean that these temperature changes are a lower bound on the actual values. This study underlines the scientific significance of the *Challenger* expedition and the modern Argo Programme and indicates that globally the oceans have been warming at least since the late-nineteenth or early-twentieth century.

The voyage of HMS *Challenger*[7,8], 1872–1876, was the first globe-circling study of the oceans, obtaining multidisciplinary data along a 69,000-nautical-mile track. "One of the objects of the Expedition was to collect information as to the distribution of temperature in the waters of the ocean … not only at the surface, but at the bottom, and at intermediate depths"[3]. The thermal stratification of the oceans was described for the first time from about 300 temperature profiles made using pressure-protected thermometers. The *Challenger* temperature data set was still prominent in large-scale maps and analyses even into the 1940s (ref. 9). Nothing remotely comparable to the *Challenger* expedition was undertaken until the 1920s–1950s, when the *Meteor*[10], *Discovery*[11], *Discovery II*[11], and *Atlantis*[12] systematically explored the Atlantic and Southern oceans.

Although the *Challenger* temperature profiles were global in scale, as they were made along the vessel's track they were not global in the sense of areal sampling. The modern-day Argo Programme, by contrast, is the first globally and synoptically sampled data set of temperature and salinity. Argo's free-drifting profiling floats collect more than 100,000 temperature/salinity profiles per year, nominally every 3° of latitude and longitude, every 10 days and to depths as great as 1,980 m.

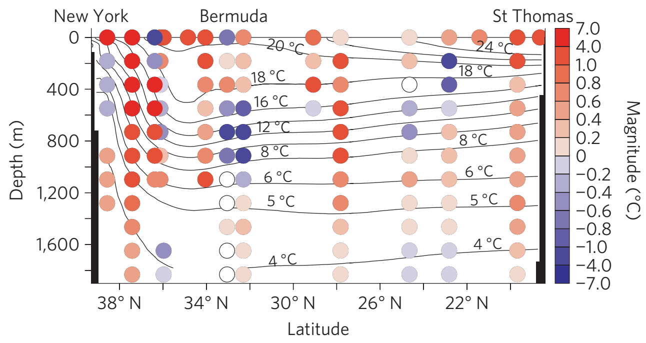

Figure 1 | New York–St Thomas transect differences. Background contours indicate mean temperature (2004–2010) from Argo data[14] along the *Challenger*'s New York to Bermuda to St Thomas transect. Colour spots show where Argo values are warmer (red), unchanged (white), or cooler (blue) than *Challenger*, with magnitudes according to the colour scale.

When qualitatively comparing features of the *Challenger* transect from New York to Bermuda to St Thomas with nearby tracks sampled in the 1950s, C. Wunsch observed "One is hard pressed to detect any significant differences on the large scale"[13]. Now, with an added 50-year interval, a quantitative comparison is made by interpolating Argo data[14] to the location and depth of each *Challenger* measurement and to the same time of year, to minimize seasonal sampling bias in the *Challenger* data set (Fig. 1). Warming is predominant from the sea surface to below 1,800 m. The largest values are in the Gulf Stream (about 38° N), indicating that the current is at a higher latitude in the Argo data than in the *Challenger* data. Obviously, these local differences may represent any timescale in the 135-year interval—from a transient meander of the Gulf Stream in 1873 to a long-term change in the current's latitude. Similarly, regional to ocean-scale differences may be affected by interannual to decadal[15,16] variability, including in the deep ocean[17], and hence our *Challenger*-to-Argo difference based on stations along the *Challenger* track must be viewed with caution.

Seasonally adjusted Argo-minus-*Challenger* differences reveal warming in both the Atlantic and Pacific oceans (Fig. 2a). The *Challenger* made only a few stations in the Indian Ocean, all at high southern latitudes, so that region is omitted here. Out of 273 *Challenger* temperature stations analysed, the Argo-era sea surface temperature (SST) is higher at 212. The mean SST difference is 1.0 °C ± 0.11 for the Atlantic and 0.41 °C ± 0.09 for the Pacific Ocean. As the *Challenger*'s sampling was more intensive in the Atlantic and the warming may be greater in that ocean, we estimate the global difference as the area-weighted mean of the Atlantic and Pacific values, 0.59 °C ± 0.12. There are extensive historical measurements of SST, providing context for the Argo-minus-*Challenger* comparison

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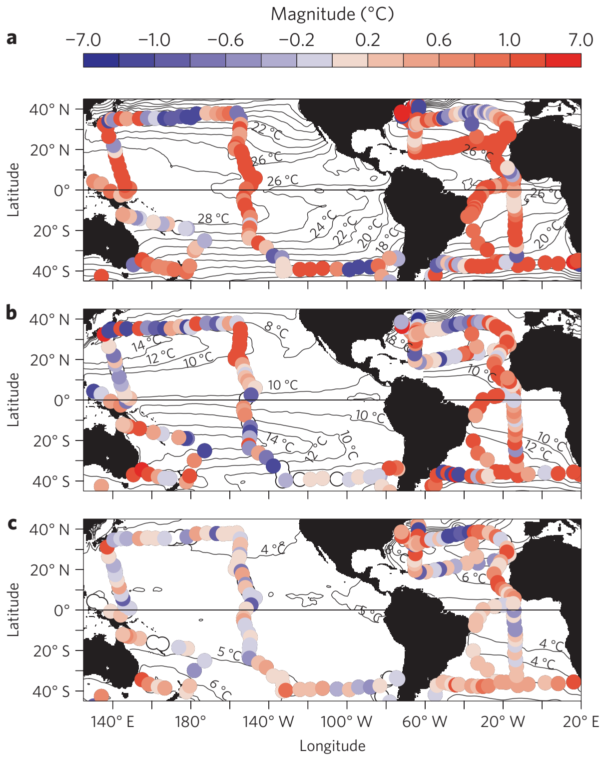

Figure 2 | Spatial differences. Background contours indicate the mean temperature (2004–2010) from Argo data[14] at the sea surface (**a**), 366 m (**b**) and 914 m (**c**). Colour spots indicate the Argo-minus-*Challenger* temperature difference, as in Fig. 1; the colour scale is shown above.

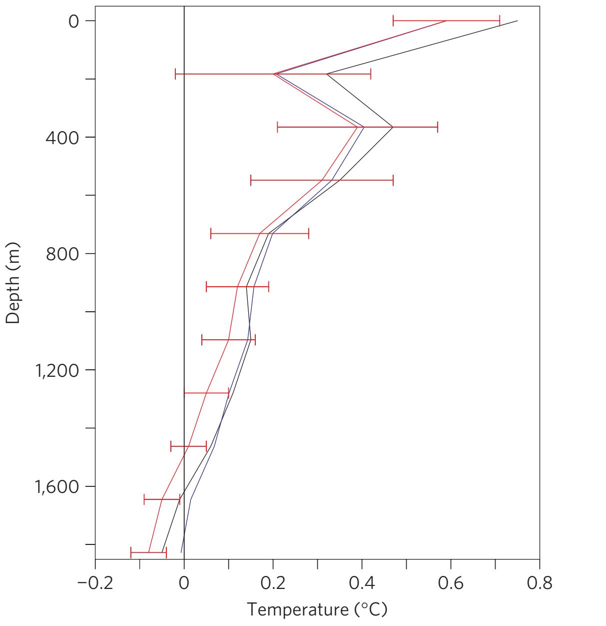

Figure 3 | Globally averaged difference. Mean Argo-minus-*Challenger* temperature difference ±1 s.e.m. The black line is a simple mean over all stations with data at 183-m (100-fm) intervals. The red line uses values for the Atlantic and Pacific oceans in a weighted mean, with weights proportional to the area of the two oceans. The blue line applies the Tait pressure correction[19] (−0.04 °C km^{-1}) to the weighted mean. Error estimates are described in Methods.

. A time series of reconstructed global mean SST from 1856 to the present day[5] indicates a cooling of SST from 1880 to 1910, with larger warming since 1910. The overall warming[5] between the *Challenger* and Argo eras of about 0.5 °C is consistent with the Argo-minus-*Challenger* estimate, given the sampling errors.

Most of *Challenger*'s subsurface temperature measurements were made using Six's (Miller–Casella) thermometers. These are maximum/minimum thermometers, with the mercury column displacing a sliding index to record the maximum or minimum temperature, and are fitted with an external bulb to remove the influence of pressure. These instruments were used in the initial belief that temperature decreased monotonically with increasing depth, an assumption discovered to be incorrect during the voyage. Other types of thermometer were used less often, including reversing thermometers that became commonplace later. The Six's thermometers were graduated in increments of 1° F (0.56 °C) and "the length occupied by one degree (F) could not easily have been subdivided beyond a quarter"[3]. Hence the temperature, which was recorded to a precision of 0.1° F (0.06 °C), had a reading accuracy of about 0.14 °C. In the report of results[18], the type and serial number of thermometers used on each station are not specified. The sounding line was 8-mm-diameter hemp, with a bottom weight of 25–75 kg (ref. 3). During the measurements the line was "…kept quite perpendicular for 5 min…" and after recovery the thermometers were "…carefully read and registered…and …corrected for errors of zero point…and a curve of temperatures drawn". It is noted that if there were outliers "…the temperatures at those depths were taken again"[3]. The *Challenger* also deployed water-filled and mercury-filled piezometers, constructed like unprotected Six's thermometers with one end open[3]. Together with data from the protected thermometers, these could be used to estimate depth. However, the ratio of temperature to depth sensitivity of these instruments was 1 °C for 783 m of depth change[3], so they were useful for correcting only large errors in near-bottom depths. The *Challenger* data listings[18] do not explicitly state that the fathom (fm) values are uncorrected line-out, but this is evident because the 100-fm and other evenly spaced increments in the data records were obtainable only by measuring and marking the sounding line.

Three sources of systematic error are considered in the *Challenger* subsurface data. First, taking depth from line-out overestimates the true depth of the thermometer, resulting in a warm bias in the recorded temperature. "If there be a current of any appreciable force, the sounding line begins to wander about, and has to be followed by the ship…an operation of considerable delicacy, even in good weather"[3]. Second, before the *Challenger*'s voyage, laboratory measurements of pressure effects on the *Challenger* thermometers had been made erroneously[19]. The post-voyage analysis by P. Tait showed that the actual compression effect on the protected glass thermometers was about 0.04 °C km^{-1} (0.3° F per 2,500 fm; ref. 19), much less than the prevoyage estimates. We therefore used the raw temperature data[18] rather than the overcorrected version listed in other *Challenger* reports. Finally, the *Challenger* thermometers were mounted in their frames using vulcanite, compression warming of which might be transferred to the glass, causing a small warm bias in the reading[19]. Thus, the errors in depth and temperature all tend to make the *Challenger* temperatures systematically warm at the recorded depths. A small number of temperature measurements were discarded in our analysis. Stations at high southern latitude were excluded owing to the shallow-temperature minimum found there and at a few other locations where Argo indicates a temperature minimum, making them incompatible with the use of maximum/minimum thermometers. The lack of high-latitude and Indian Ocean stations could produce a sampling error in global averages, as multidecadal ocean warming is known to have been strong in the Southern Ocean since the 1930s (ref. 20) as well as having substantial basin-to-basin differences[17]. Error bars on our estimates of globally averaged temperature differences are discussed in the Methods section.

Table 1 | Summary of data, including depth, s.d. of Argo-minus-*Challenger* differences and the number of *Challenger* stations used in the analysis.

Depth (fm)	0	100	200	300	400	500	600	700	800	900	1,000
s.d. (°C)	1.14	1.85	1.58	1.3	0.91	0.59	0.43	0.36	0.31	0.28	0.26
No. stations	273	220	220	210	202	200	176	168	168	159	149

A listing of the *Challenger* data used and the temperature differences is provided as Supplementary Information.

Proceeding downwards to 366 m (200 fm, Fig. 2b) and 914 m (500 fm, Fig. 2c), the pattern of mostly warm differences persists in both oceans, diminishing in magnitude with depth. The global average temperature difference (ocean area weighted) decreases to 0.39 °C ± 0.18 at 366 m and 0.12 °C ± 0.07 at 914 m, reaching zero at about 1,500 m (Fig. 3).

For the upper 700 m, the ocean area-weighted difference, using only those stations with samples every 183 m, is 0.33 °C ± 0.14, corresponding to a heat gain of 1×10^9 J m^{-2}. This increases to 1.3×10^9 J m^{-2} for 0–1,500 m, or 0.3 W m^{-2} of ocean surface area, averaged over the 135-year interval. The average differences, 0–700 m, are 0.58 °C ± 0.12 for the Atlantic and 0.22 °C ± 0.11 for the Pacific Ocean. The Tait pressure correction[19], equivalent to −0.04 °C km^{-1} would increase these values by only 4%. The temperature bias caused by depth errors is difficult to assess, but may be significant at locations such as the equatorial Pacific, where the strong subsurface shear of the Equatorial Undercurrent, not known in *Challenger*'s time, would cause a slant in the line. Evidence of this bias can be seen (Fig. 2a,b) where temperature differences change from positive to negative between the sea surface and 366 m at near-equatorial Pacific stations. A systematic overestimate of 1% in the depth of *Challenger* measurements would result in a warm bias in the 0–700 m average temperature of about 0.05 °C.

The *Challenger* temperature measurements are known to be far from perfect and were the subject of controversy as instanced in the correspondence between J. Murray and W. Leighton Jordan in the late 1880s (ref. 21). However, the data were collected with great care and attention, and the large temperature changes over the subsequent 135 years are revealed by comparing the *Challenger* and Argo data sets.

We find that the modern upper ocean is substantially warmer than the ocean measured by HMS *Challenger* in the 1870s and that the warming signal is global in extent. *Challenger* obtained enough measurements of temperature for statistical confidence at about the 95% level in the mean temperature differences and the nature of systematic errors in the *Challenger* data makes these differences a lower bound on the true values. Moreover, comparisons with other temperature records including global SST (ref. 5), extensive subsurface data in the Atlantic as early as the 1920s (ref. 22) and global subsurface data over the past 50 years[6], all indicate that the warming has occurred on the centennial timescale rather than being limited to recent decades. From 1969 to 2009, globally distributed temperature measurements, 0–700 m, showed warming of an average of 0.17 °C (ref. 6), with the Atlantic Ocean warming more strongly (0.30 °C) than the Pacific (0.12 °C). The larger temperature change observed between the *Challenger* expedition and Argo Programme, both globally (0.33 °C ± 0.14, 0–700 m) and separately in the Atlantic (0.58 °C ± 0.12) and Pacific (0.22 °C ± 0.11), therefore seems to be associated with the longer timescale of a century or more.

The implications of centennial-scale warming of the subsurface oceans extend beyond the climate system's energy imbalance. Thermal expansion is a substantial contributor to global sea-level rise[23–25] and extending the record length of subsurface temperature can help in the understanding of the centennial timescale in sea-level rise[26,27]. Furthermore, changes in subsurface temperature and in SST are closely related. SST is important in determining air–sea exchanges of heat and increasing SST is linked to increasing rates of evaporation, and hence precipitation, in the global hydrological cycle[28,29]. The long-term increase of SST should be understood in the context of changes in both temperature and salinity extending deep into the water column.

Enormous advances in ocean-observing technology have occurred from the time of the *Challenger*, when about 300 deep-ocean temperature profiles were acquired over three-and-a-half years by a ship with more than 200 crew on board, to today's Argo Programme, obtaining more than 100,000 temperature profiles annually by autonomous instrumentation. The *Challenger* data set was a landmark achievement in many respects. With regard to climate and climate change, *Challenger* not only described the basic temperature stratification of the oceans, but provided a valuable baseline of nineteenth-century ocean temperature that, along with the modern Argo data set, establishes a lower bound on centennial-scale global ocean warming.

Methods

Consecutive *Challenger* stations were typically spaced 100–300 km apart (Fig. 1) and separated by a few days to months. From the standpoint of mesoscale eddy noise, the temperature data might be considered to be independent from station to station. However, regional variability in temperature and heat content on interannual[30] to decadal[17] timescales is noise in the context of our 135-year *Challenger*-to-Argo difference. To estimate the reduction in the number of independent data points, we divided the multiyear *Challenger* track into seven continuous segments, four in the Atlantic and three in the Pacific, and calculated the along-track autocorrelation of the *Challenger*-to-Argo temperature differences as a function of the number of stations of separation. The sample autocorrelation has a narrow peak at all depths, but a low tail extending from three to five stations before decreasing to zero. Taking twice the integral of the autocorrelation gives a correlation scale of three stations at the sea surface, decreasing to two at 500 fm. For simplicity, we use three stations as the correlation scale at all depths. The standard error (s.e.m.) of the *Challenger*-to-Argo difference was then estimated as the standard deviation (s.d.) divided by the square root of the number of degrees of freedom (NDF), where NDF was the number of stations divided by three. Table 1 lists the s.d. of the temperature difference at each depth together with the number of stations. For the differences in 0–700 m average temperature (and difference in heat content) we used the s.d. of 0–700 m average temperatures, and again NDF is one-third of the number of stations that have data every 100 fm over this depth range. Errors listed in the manuscript are one s.e.m.

Received 18 January 2012; accepted 27 February 2012; published online 1 April 2012

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Acknowledgements

We acknowledge the beginning of global oceanography by HMS *Challenger* and the 140th anniversary in 2012 of its departure from Sheerness, Kent, UK, on 7 December 1872. The Argo data used here were collected and are made freely available by the International Argo Programme and by the national programmes that contribute to it. D.R. and J.G. and their part in the Argo Programme were supported by US Argo through NOAA grant NA17RJ1231 (SIO–JIMO).

Author contributions

D.R. conceived the study, directed the analysis and was lead writer. W.J.G. surveyed the *Challenger* reports, extracted the data and wrote parts of the manuscript. J.G. carried out the calculations, including averaging and interpolation of Argo data and error estimates, created figures and contributed manuscript revisions.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to D.R.